Application of Fracture Mechanics to the Welded Joints of HT80 Steel for Penstock Use †

Kohsuke HORIKAWA* and Toshie OKUMURA**

Abstract

Fracture mechanics has been applied to the determination of toughness requirements on welded joints of HT80 steel plates, with thickness of up to 100 mm, for the huge penstocks of 1000 MW pumping up hydroelectric power stations. This paper presents the short introduction of history of establishment of the requirements and makes some discussions on these requirements.

KEY WORDS: (Fracture Mechanics) (Brittle Fracture) (Toughness) (Penstock) (Low Alloy Steel) (QT Steel)

1. Introduction

Since 1969, five pumping up hydroelectric power stations of 1000 MW output have been constructed, and further one is now under construction, and several are planned.

These big power stations demand huge penstocks. **Table 1** shows the dimensions of these penstocks.

These huge penstocks are accomplished only by using high strength steel with 686 N/mm^2 (70 kg/mm^2) or 784 N/mm^2 (80 kg/mm^2) tensile strength, with thickness of up to 100 mm for plates and 350 mm for forged reinforcing rings of branches.

The developments of these high strength steels have been made under following procedures:

1) Target properties were set after intensive analysis on former projects, with a prospect of improvement.

2) Sample plates were produced, welded joints were fabricated with planned welding procedures and conditions, and then various tests were conducted.

3) Target properties were modified after the results of the tests, and specifications were determined considering the scatter at mass production.

4) Mill sheet data on mass produced plates supplied were collected and analysed for following projects.

Fracture mechanics was applied for the analysis of fracture toughness of welded joints as well as base metal.

This paper introduces how fracture mechanics was applied to the determination of specifications of high strength steel for penstock use.

Table 1. Dimensions of Penstocks

Name of Station	Pressure Head	Diameter	Steel Grade	Max. Plate Thickness	Year of Operation
Numahara	687.8 m	2.60 m	HT70	34 mm	1972
Ohira	753.9	2.60	HT80	36	1975
Nabara	517.0	3.50	HT80	32	1976
Okukiyotsu	654.9	4.00	HT80	75	1977
Okuyoshino	833.0	4.30	HT80	78	1978
Okuyahagi No.2	600.0	5.50	HT80	91	to be 1980

† Received on March 31, 1979
* Associate Professor
** Professor, Saitama University

2. Base Metal Properties

2.1 Chemical Composition

Specifications of chemical composition and results of ladle analysis on sample plates are shown in **Table 2** and 3, respectively,

where

$$Ceq = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14 \qquad (1)$$

$$Pcm = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B \qquad (2)$$

C and Ceq were reduced as low as possible in order to prevent weld cracking, while considerable amount of Ni was added to sustain fracture toughness of fusion line of welded joints, as discussed later. To compensate low C content, B was also added for hardinability.

Table 2. Specifications for Chemical Compositions

Name of Station	Steel Grade	Plate Thickness	Chemical Compositions [%]										
			C	Si	Mn	P	S	Ni	Cr	Mo	V	B	Ceq
Numahara	HT70	*	≦0.14	≦0.50	≦1.10	≦0.015	≦0.015	0.90 −1.50	≦0.60	≦0.60	≦0.07	–	≦0.49
Ohira	HT80	*	≦0.14	–	–	≦0.015	≦0.015	≒1.0	–	–	≦0.05	≦0.005	≦0.53
Nabara	HT80	*	<0.13	–	–	≦0.015	≦0.015	≒1.0	–	–	<0.05	<0.005	<0.52
Okukiyotsu Okuyoshino	HT80	≦50 mm 50–100	≦0.14	–	–	≦0.015	≦0.015	≒1.0	–	–	≦0.05	≦0.005	≦0.53 ≦0.57
Okuyahagi No. 2	HT80	≦50 50–100	≦0.14	–	–	≦0.015	≦0.015	**	–	–	≦0.05	≦0.005	≦0.53 ≦0.57

* Maximum plate thicknesses were 41, 36, 32 mm respectively.

** Considerable amount of alloys should be added.

Table 3. Ladle Analysis Results of Sample Plates

Mark	Steel Grade	Plate Thickness	Chemical Compositions [%]											
			C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B	Ceq	P cm
A1	HT70	35 mm	0.10	0.32	0.80	0.012	0.008	0.03	1.35	0.32	0.39	0.03		0.44	0.22
A2	HT70	42	0.11	0.32	0.79	0.013	0.010	0.03	1.31	0.42	0.47	0.03		0.49	0.24
B	HT80	36	0.11	0.26	0.76	0.010	0.007	0.22	0.97	0.51	0.46	0.04		0.49	0.25
C	HT80	34	0.10	0.25	0.87	0.006	0.005	0.23	1.04	0.51	0.37	0.03	0.001	0.48	0.24
D1	HT80	50	0.13	0.31	0.91	0.010	0.008	0.24	1.03	0.45	0.41	0.05		0.52	0.27
D2	HT80	75	0.12	0.26	0.89	0.009	0.007	0.27	1.51	0.51	0.49	0.05		0.55	0.28
E1	HT80	50	0.11	0.23	1.00	0.014	0.006	0.20	0.97	0.43	0.36	0.03	0.003	0.49	0.26
E2	HT80	75	0.12	0.25	0.85	0.013	0.010	0.23	0.98	0.42	0.46	0.03	0.002	0.50	0.26
F1	HT80	50	0.11	0.26	0.85	0.006	0.006	0.18	0.96	0.50	0.43	0.04	0.001	0.50	0.25
F2	HT80	50	0.10	0.31	0.90	0.007	0.005	0.26	1.03	0.47	0.47	0.03	0.001	0.50	0.25
F3	HT80	78	0.12	0.25	0.85	0.007	0.005	0.22	1.20	0.56	0.47	0.04	0.002	0.54	0.28
F4	HT80	78	0.13	0.28	0.86	0.008	0.006	0.23	1.29	0.47	0.47	0.04	0.001	0.53	0.28
G	HT80	100	0.12	0.27	0.89	0.008	0.005	0.24	1.43	0.52	0.48	0.03	0.002	0.54	0.28

2.2 Mechanical Properties

Specifications of mechanical properties and test results on sample plates are shown in **Table 4** and **5**, respectivley. In **Figure 1** are V-Charpy transistion curves, and **Figure** 2 shows results of Double Tension tests on sample plates. Specimens were taken crosswise to roll direction at top side and ¼T of plates except tensile specimens of B, C, D1 and E1. B, D1 and E1 were through thickness. C was from ½T.

Specification of tensile properties for HT80 was determined after T-1 steel, while that for HT70 was rather arbitrary. For Honshu Shikoku Connecting Bridges, whose specifications have been determined after studies on these penstock data, yield strength is modified as not less than 588 N/mm^2 (60 kg/mm^2), even ultimate strength is not less than 686 N/mm^2 (70 kg/mm^2).

Specification of notch toughness was determined after Grade A (Arrest use) of WES 136-1964, with interpretation that half of V-Charpy absorbed energy at room temperature is to be 35.3 J (3.6 kg.m) or 47.0 J (4.8 kg.m). WES 136-1964 was revised in 1973. But specification for penstock was not revised, since V-Charpy tests were used for quality control only. Test data on supplied plates showed enough margin, when plates were produced with specified chemical composition determined to sustain fracture toughness of fusion line of welded joints as well as the base plate.

Table 4. Specifications for Mechanical Properties

Name of Station	Steel Grade	Plate Thickness	Tensile Properties		Notch Toughness	
			Yield Strength	Ultimate Strength	vE-35	vE-40
Numahara	HT70	*	≧617 N/mm²	686-804 N/mm²	≧vE$_{RT}$/2	
Ohira Nabara	HT80	*	≧686	≧784		≧35.3 J
Okukiyotsu	HT80	<50 mm 50-100	≧686 ≧666	784-931 764-911		≧35.3
Okuyoshino	HT80	<50 50-100	≧686 ≧666	≧784 ≧764		≧35.3
Okuyahagi No. 2	HT80	<50 50-100	≧686 ≧666	784-931 764-911		≧47.0

* Maximum plate thicknesses were 41, 36, 32 mm respectively.

Table 5. Mechanical Properties of Sample Plates

Mark	Steel Grade	Plate Thickness	Tensile Properties				Notch Toughness		
			Yield Strength	Ultimate Strength	Elongation	Shape of Specimen	vE-35	vE-40	vTrs
A1 A2	HT70	35 mm 42	627 N/mm² 764	696 N/mm² 813	26 % 23	JIS-4 JIS-4	191 J 137		−64°C −55
B C	HT80 HT80	36 34	774 715	823 794	21 25	JIS-1B JIS-4		84 J 208	−40 −97
D1 D2	HT80	50 75	774 784	843 823	38 21	JIS-5 JIS-4		94 96	−91 −85
E1 E2	HT80	50 75	843 735	902 794	31 26	JIS-5 JIS-4		128 147	−88 −81
F1 F2 F3 F4	HT80	50 50 78 78	774 804 804 784	823 843 853 833	26 23 24 23	JIS-4 JIS-4 JIS-4 JIS-4		162 132 140 161	−80 −74 −77 −80
G	HT80	100	755	813	24	JIS-4		171	−95

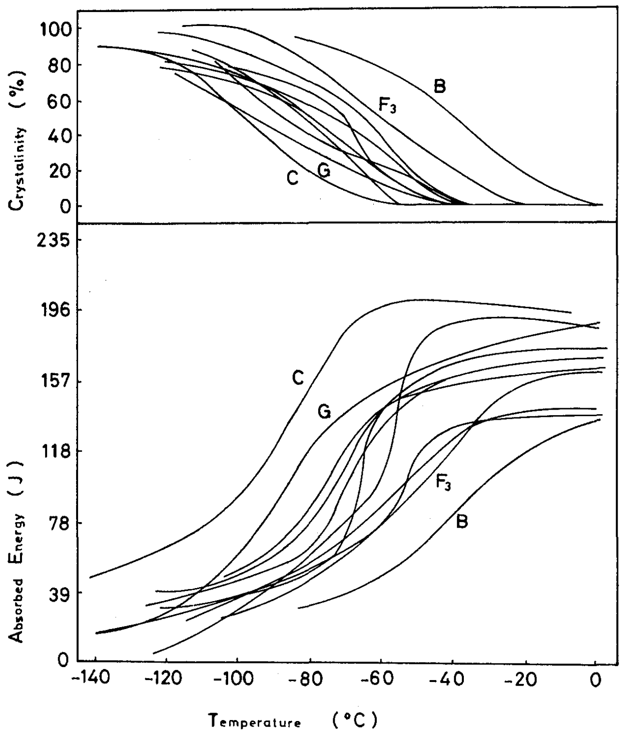

Figure 1. V-Charpy Transition Curves

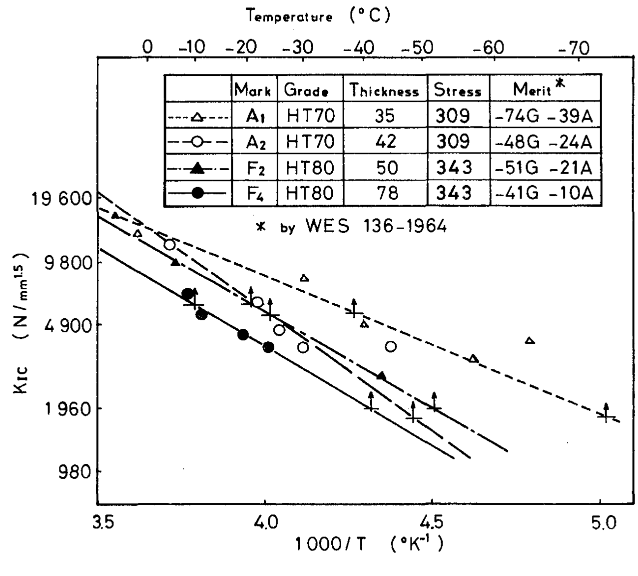

Figure 2. Results of Double Tension Tests.

3. Toughness of Welded Joints

3.1. Requirements on Toughness

Notch toughnesses shown in **Table 6** were announced as requirement for welded joints, but not specified, because they can not be tested on each joint.

In welded joints, the weakest part is fusion line, or what we call bond, so these requirements were discussed for fusion line.

Table 6. Requirement on Toughness of Welded Joints

Name of Station	Requirement
Numahara	vTrs $\leqq$ 0°C
Ohira	vEo $\geqq$ 35.3 J or $K_{IC} \geqq$ 3 371 N/mm$^{1.5}$ at −70°C
Nabara	vEo $\geqq$ 35.3 J or S_i $\geqq$ 35.9 J/mm^2 at −70°C
Okukiyotsu	vEo $\geqq$ 35.3 J
Okuyoshino	vEo $\geqq$ 35.3 J
Okuyahagi No. 2	vEo $\geqq$ 47.0 J

Numahara requirement was determined after Grade G (General use) of WES 136-1964. Grade G of WES (1964 edition) was specified to assure the ability to arrest the propagation of crack of 2C = 20 mm.

At discussion for Ohira requirement, it was concluded that requirement should be drawn from the consideration on initiation characteristics. Deep Notch test was adopted for assessing initiation characteristics, and $\sigma_y/2$ (Ti) C = 40 was uded as index of fracture toughness, which is the temperature of brittle fracture initiation from a through thickness crack of 2C = 80 mm. Although such a large crack is hardly found, this was used for the convenience of comparision with former data. At this temperature fracture toughness is calculated as

$$K_{IC} = \sigma\sqrt{\pi C} = 343\sqrt{3.14 \times 40} = 3\ 842 \text{ N/mm}^{1.5} \quad (3)$$

In spite service temperature is not less than 0°C, reference temperature was set at −80°C, considering temperature rises of 50°C due to residual stress and 30°C due to imperfections such as missalignment and angular distortion.

Sample plate B for Ohira project gave $\sigma_y/2$ (Ti)$_C$ = 40 = −80°C, just the refernence temperature.

Then through thickness crack was considered too severe, and replaced by more practical crack, namely, surface crack of 9 mm in depth and 60 mm in length, which was found in a fractured spherical tank [1].

Required fracture toughness was calculated by following equation [2].

$$K_{IC} = f(C/B)\frac{t_1}{t}\sigma\sqrt{\pi C} + 6Y_B\frac{f(C/B)}{f(t_1/t)}\frac{t_1}{t}\sigma\sqrt{C} \quad (4)$$

where

$$f(C/B) = \sqrt{\frac{2B}{\pi C}\tan\frac{\pi C}{2B}} \qquad f(t_1/t) = \sqrt{\frac{2t}{\pi t_1}\tan\frac{\pi t_1}{2t}}$$

$$Y_B = 1.99 - 2.47(t_1/t) + 12.97(t_1/t)^2 - 23.17(t_1/t)^3 + 24.80(t_1/t)^4$$

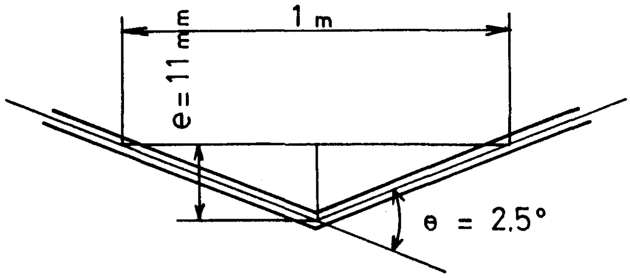

Figure 3. Definition of Angular Distortion

and

2C = 60 mm: crack length
t_1 = 5 mm: crack depth
e = 11 mm/m: angular distortion (see **Figure 3**)
B = 600 mm: width of test specimen
t = 36 mm: plate thickness
σ = 441 N/mm^2: gross stress (restraint stress 127/N/mm^2 is added to the design stress 314 N/mm^2)

Calculated stress intensity factor was 3 371 N/mm$^{1.5}$.

Testing temperature was set −70°C considering temperature rise due to residual stress and missalignment, as distortion was already taken into account in Eq. (4).

Surface notch wide plate tension test and Deep Notch test demand so many test plates that they are not preferred even at procedure test. So primary assessment was done by V-Charpy test with reference value of vEo $\geqslant$ 35.3 J (3.6 kg.m). This was after WES Grade G, and half of absorbed energy at room temperature was read as 35.3 J. Deep Notch test or surface notch wide plate tension test was only required for final conformation and in case when V-Charpy reference value was missed.

Si $\geqslant$ 35.9 J/mm^2 for Nabara requirement is same as $K_{IC} \geqslant$ 3 842 N/mm$^{1.5}$ (see Eq. (3)).

Okukiyotsu and Okuyoshino followed Ohira in philosophy, but only V-Charpy reference values were announced:

By using Eq. (4), K_{IC} requirement for reinforcing ring of Okuyahagi station was calculated as small as 58.8 N/mm$^{1.5}$. This is because thickness of reinforcing ring is 345 mm, and notch depth was assumed as 5 mm, so t_1/t in Eq. (4) reduced to 0.014. Eq. (4) was derived from experiments on the plates with thickness of 20 to 30 mm. So 345 mm is out of application range.

Eq. (5) was then adopted for not only reinforcing ring but also plates. This equation was derived after numerical calculations by KOBAYASHI A. S. [3].

$$K_I = [M_{Tf} \times M_{Tb} \times \sigma n + M_B \times \sigma_B] \times t_1/E(b) \quad (5)$$

where

$$M_{Tf} = 1.12 - 0.12b + 0.03b^2$$

$$M_{Tb} = 1.0 + 0.127a - 0.079b - 0.558a^2 - 0.175ab + 0.279b^2 + 1.44a^3 - 1.06a^2b + 0.609ab^2 - 0.249b^3$$

$$M_B = 1.183 - 1.22a - 0.286b + 0.867a^2 - 0.006\,77ab + 0.23b^2 + 0.467a^3 - 1.92a^2b + 0.633ab^2 - 0.182b^3$$

$$a = t_1/t \qquad b = t_1/C$$

$$E(b) = \int_0^{\pi/2} [1 - (1\text{-}b^2)\sin^2\theta]^{1/2}\, d\theta$$

and σn = 314 N/mm^2: design stress

$\sigma_B = (6e/t) \times \sigma n$: bending stress due to angular distortion

t_1 = 5 mm: depth of crack

2C = 85 mm: crack length

This crack size was set after periodical shut down inspection on spherical tanks [4].

t = 100 mm: plate thickness

e = 11 mm/m: angular distortion (see Figure

Calculated stress intensity factor was 2 127 N/mm$^{1.5}$. While test results on the sample plates were 3 508 N/mm$^{1.5}$ for SAW joints and 4 488 N/mm$^{1.5}$ for MIG joints.

V-Charpy reference value was announced as 47.0 J(4.8 kg.m), as half of absorbed energy at room temperature was read as 47.0 J.

3.2 Discussion

Comparing assumptions at above calculations for Ohira and Okuyahagi, assumed crack size and applied stress for Ohira were larger than those for Okuyahagi. When Eq. (5) was employed together with Ohira's assumption by the author, K_{IC} = 4 145 N/mm$^{1.5}$ is obtained.

Angular distortion e = 11 mm/m was set after the Standard Specification of the Water Gate and Penstock

Table 7. Comparison of Estimated Fracture Toughness

Equation	Crack Length	Crack Depth	Distortion	Restraint Stress	Plate Thickness	Calculated K_I	Remarks
3	80 mm	Through Thickness	–	0	–	3 842 N/mm$^{1.5}$	
4	60	9 mm	11 mm/m	127 N/mm^2	36 mm	3 371	Ohira Requirement
5	60	9	11	127	100	4 145	
5	60	9	11	0	100	3 012	
5	60	9	5	127	100	3 391	
5	85	5	11	127	100	2 978	
5	85	5	11	0	100	2 127	Okuyahagi Requirement

Table 8. Fracture Toughness of Welded Joints

Mark	Steel Grade	Plate Thickness	Welding Procedure	Heat Input	$\sigma y/2^{(Ti)}$ C=40	K_{IC} at –70°C	Test Method
A1 A2	HT70	35 mm 42	S A W	40 KJ/cm 40	–115°C –118	5 194 N/mm$^{1.5}$ 5 331	Deep Notch
B D2	HT80 HT80	36 75	S A W S A W	52 45-48	–80 –113	4 194 5 674	Deep Notch Deep Notch
F1 F2	HT80	50 50	S A W S A W	49.4 40	–99 –85	4 714 4 449	Deep Notch
G Gm	HT80	100	S A W M I G	46.9 23.5	–50 –80	3 508 4 488	W O L

Association, but in most of constructed penstocks distortion e was not more than 5 mm/m. The results of calculations on several combinations of assumptions are as in **Table 7.** From these calculations, required fracture toughness might be estimated as not less than 2 940 $N/mm^{1.5}$ (300 $kg/mm^{1.5}$) and not more than 3 920 $N/mm^{1.5}$ (400 $kg/mm^{1.5}$).

Figure 4 and **Table 8** show the test results on sample plates. Mark Gm was welded by MIG, others were welded by SAW. Mark G and Gm were results of WOL test, others were of Deep Notch test. **Figure 5** is the comparison of WOL test and Deep Notch test. This figure shows good agreement between them.

Figure 6 show relationship between fracture toughness data and V-Charpy data. They show good correlations, except Mark G and Gm, whose fracture toughness were gained from WOL test.

From these considerations the V-Charpy reference value vEo = 47.0 J(4.8 kg.m) can be understood as reasonable.

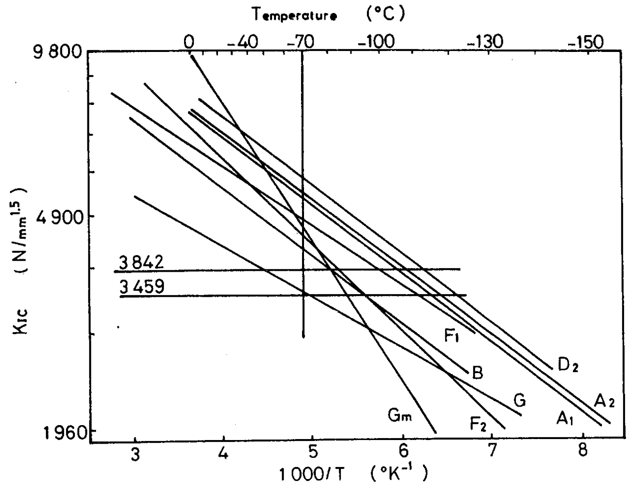

Figure 4. Fracture Toughness of Welded Joints

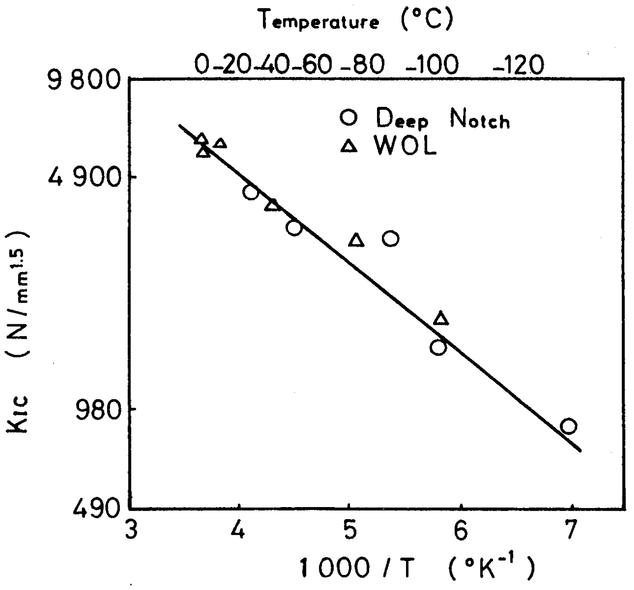

Figure 5. Relations between Deep Notch Tests and WOL Tests.

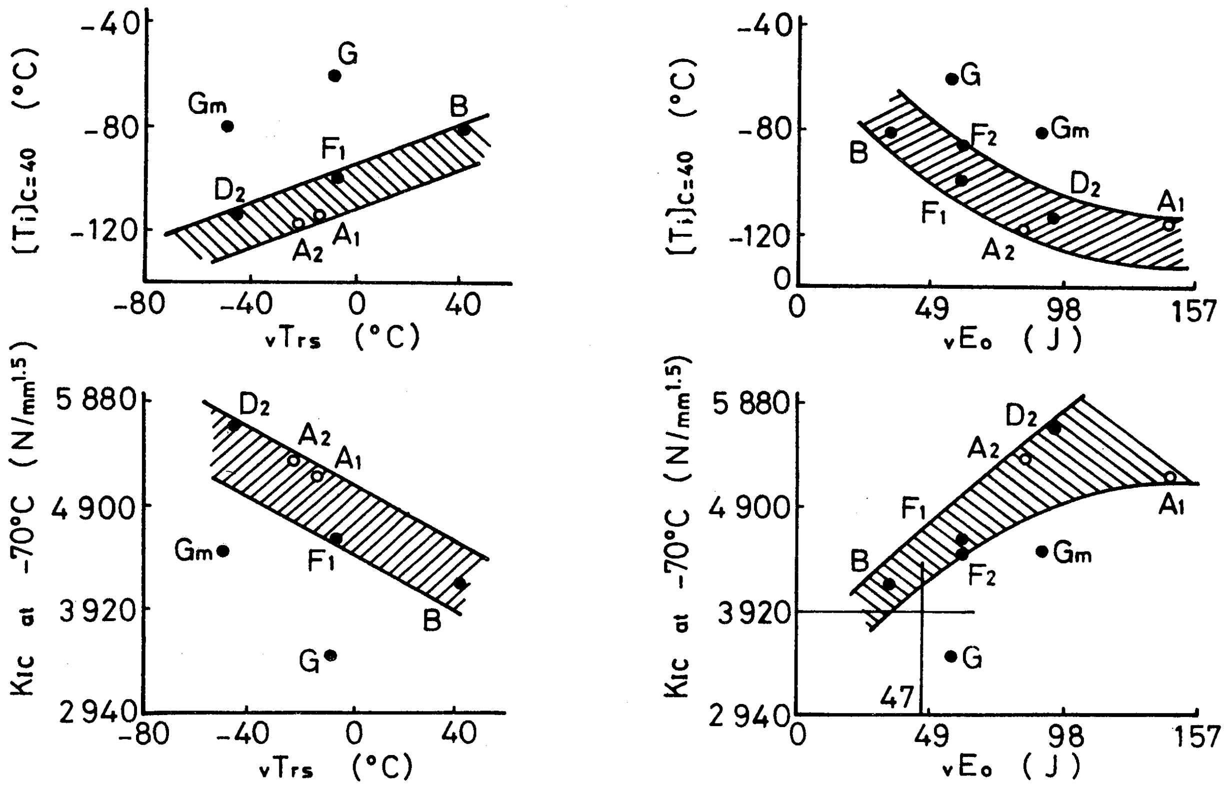

Figure 6. Relations between Fracture Toughness Data and V-Charpy Data

4. Closing Remarks

All of these penstocks have been constructed satisfactory, and power stations are in operation today.

The authors acknowledge the owners of the power stations, fabricators, and steel makers for their cooperations.

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